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Edwards Street Laboratory
Yale University
New Haven, Connecticut

ESL Technical Memorandum No. 21
(ESL 521: Ser 5)
4 November 1953

Notes on the Analysis of Low-Frequency
Ambient Signals

R. W. Jackson

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Date: 12/24/53 *C. E. Lundgren*
By direction of
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For the development of certain undersea electrical apparatus (see TR 11) it was felt desirable to obtain some information on the spectrum of the ambient electrical signals in the sea in the range 2 to 50 c/s. Some recordings on magnetic tape were made by Dyba, Strickler, and Wadey for analysis at a later time when a low-frequency spectrum analyser became available. Although the instrument they had in mind for the analysis has been obtained, the analyses have not been carried through, and the plan has been shelved for the time being, for reasons which will be apparent from the following discussion. The associated problems will be discussed in some detail in case the work should be resumed at some future time.

The characteristics of the Muirhead-Pametrada Wave Analyser are such that the frequency range 2 to 50 c/s can be covered only by a combination of two methods. The response of the instrument extends downwards to 19 c/s. The range from 2 to 19 c/s must then be analysed by means of an auxiliary Modulator Unit which beats the input signal against the power-line frequency of 60 c/s, allowing the Wave Analyser to work in the range 62 to 79 c/s. The 6 db bandwidth of the Wave Analyser is $\pm 1\%$ (i.e., the bandwidth is 2% of the center frequency). The 3 db bandwidth is approximately $\pm 0.7\%$. It follows that the limit of resolution is approximately 1.4%, which is to say that, in the vicinity of 1000 c/s, for example, two closely-spaced pure frequencies cannot be resolved if they are separated by less than 14 c/s.

Since there was no equipment available for the direct recording of frequencies in the 2 to 50 c/s range, the method was adopted by Wadey et al of combining the low frequencies with a carrier frequency f_c of the order of 1000 c/s by amplitude modulation of the carrier. The resulting frequency spectrum $f_c \pm f$, or carrier with sidebands, was then in a convenient range for recording on a Magnecorder magnetic tape recorder. The modulator circuit used was a suppressed-carrier type such that, when operating correctly, the component of carrier-frequency appearing in the output is virtually zero. The output spectrum consists of the sidebands only.

It might be thought that the frequency analysis could be most conveniently performed directly upon the above output spectrum in the region about 1000 c/s, but a glance at the resolving power of the Muirhead Analyser (14 c/s in the region of 1000 c/s) shows that such an analysis would tell us very little indeed. The spectrum, then, must be translated somehow into a lower frequency region where the relative bandwidth of the Analyser will give a sufficiently high resolution. There are a number of difficulties which appear when one considers how this should be done in practice.

The original low-frequency signal could be recovered by restoring the carrier to convert the signal to ordinary amplitude modulation, then rectifying to obtain the envelope in the usual way. But the original carrier or a signal

phase-coherent with the original carrier is not available since the recordings were made in the past. Hence the restored carrier frequency f'_c , say, would be slightly different from the original frequency f_c , and the two sidebands $f_c \pm f$ would be superimposed in the result as separate signals $f + (f'_c - f_c)$ and $f - (f'_c - f_c)$, beating together at the rate $(f'_c - f_c)$. If $(f'_c - f_c)$ were a very low frequency it would appear as fluctuations in the Analyser output, confusing the result considerably, since the amplitude of various components in the ambient spectrum might well be expected themselves to fluctuate slowly with time. If $(f'_c - f_c)$ were a higher frequency, but still at the low end of the 2 to 50 c/s spectrum, the superimposition of the two mutually displaced spectra would be likely to spoil the resolution of the Analyser. Note furthermore that it is assumed that the original carrier and the restored carrier are constant in frequency with time. In fact this will not be the case. Inspection of the type of oscillator circuit used to generate the original carrier, and of the components used in its construction shows that it is most unlikely that the carrier frequency generated would have been stable against power supply, temperature, and component variations to the necessary order of one cycle in a thousand or better. The possibility should not be ruled out of using some type of locked-in oscillator as the generator of the restored carrier, but this would be a highly specialized development which might or might not work satisfactorily.

Some of the above difficulties could in principle be obviated by passing the signal $f_c \pm f$ through a sharply-discriminating filter to pass one group of sidebands and reject the other. If it is hoped to determine the presence of frequency components as low as 2 c/s, the transition of the filter from pass band to attenuation band would have to be less than 4 c/s wide and the filter would have to be specially designed and adjusted to work at the exact frequency of the original oscillator --- which was somewhere in the neighborhood of 950 c/s.

A simpler solution would be to heterodyne the recorded signal with a second frequency f'_c , not to bring the spectrum back about the zero-frequency point, but only to bring it lower in the frequency scale than 1000 c/s. Then one would hope to locate the point corresponding to the original zero frequency by the symmetry which should show up in the analysed spectrum.

On closer examination of the actual recordings made and the equipment used to make them, the picture changes somewhat. It was found in checking the apparatus that the modulator circuit did not function in an ideal manner, being somewhat unbalanced by D-C leakage through an electrolytic coupling capacitor. It was inferred from this that there must be a substantial amount of unmodulated carrier present on all the recordings made, at least enough to give a clear peak

in the Analyser output at the center-point of the symmetrical spectrum. Thus the problem of determining the zero-point of the spectrum would probably be considerably simplified. At the same time, examination of the recorded signals as displayed on an oscilloscope showed that the amount of carrier present was not sufficient to make the signal a simple case of amplitude modulation. Had it been so, instead of partly the carrier-suppressed type, the recovery of the original low-frequency information would have been very simple. As it is, heterodyne procedures must be used. Each time the signal is subjected to a non-linear operation such as modulation or demodulation (heterodyning or rectification) it is further "muddied" by intermodulation products among the various signal frequencies. To keep the unwanted intermodulation products small care must be taken that the amplitude of the heterodyning frequency component f'_c is always large compared to the amplitudes of the signal frequencies $(f_c \pm f)$. Providing this is done however, the above method of heterodyning the recorded signals downward to a lower frequency range, say about a center frequency of 50 or 60 c/s, should recover the information from the tapes in reasonable shape.

Unfortunately, however, in the course of examining the recording apparatus to determine in just what form the information had been incorporated on the tapes, it was also found that disturbingly large amounts of 60 c/s hum were

present in the system. Part of this came from a modification which had been made in the Magnecorder amplifier to introduce a calibrated attenuation control. The trouble was corrected by careful shielding of the leads and terminals to the control. The other serious source of hum was in the modulator circuit. For output signals of average amplitude (about 1V.) from the modulator circuit the relative proportion of superimposed hum was of the order of 20%. This was reduced to a negligible level by improved shielding and revision of ground connections. However, it was surmised that the amount of hum present throughout the original recordings when made would be sufficient to generate a troublesome proportion of intermodulation distortion which would confuse the interpretation of the results. The doubts cast by this expectation, coupled with the discovery that similar experiments were being made elsewhere (Electromechanical Industries, Inc) with much superior apparatus, led us to decide that at this time our limited manpower would be better deployed on other aspects of the central problem, the development of the undersea electrical apparatus.

The examination of the recordings and the revision of the apparatus were done with the assistance of Mr. D. G. Sampson, graduate student, and Mr. M. Carrano, technician.



Ray W. Jackson

APPENDIX - (A)

Circuit Diagrams of Equipment Used

The circuit diagrams bound at the end of the report show (1) the modulator circuit revised to give simple amplitude modulation of the carrier, (2) a simple full-wave envelope detector circuit, (3) a D-C amplifier built to drive an Esterline-Angus recording milliammeter from the output of the Wave Analyser. The circuit for the latter was adapted from a circuit in "Vacuum-Tube Amplifiers" by Valley & Wallman, p. 480.

APPENDIX - (B)

Possible Advantages of FM

For the faithful recording of very low frequency signals it appears that there are a number of advantages in the use of frequency modulation rather than amplitude modulation. The Ampex Co. has put on the market a complete apparatus for recording very low frequency signals by this method. Once the frequency stability of the modulator and the constancy of tape speed have been adequately taken care of, the form in which the information is coded by frequency modulation renders the information substantially unaffected by non-linearities, microphonics, etc., in the amplifying and recording system right up to the point where the signal is finally demodulated; whereas the amplitude-modulated signal is sensitive throughout to distortion by non-linearities and to superimposed modulation from extraneous sources. There may be additional advantages to the frequency modulation system in avoiding the tendency of amplitude-modulation detectors to generate distortion at high levels of modulation. On the other hand, unless a recording mechanism of high quality such as the Ampex is available it is a debatable point whether the tape speed would be so constant that FM would be the better system. Thus if the Magnecorder is all that is available the pros and cons of the two methods should be weighed in more detail.

APPENDIX - (C)

Presentation of Results

An important question to be considered is how to display the results of the analyses in a way that can be interpreted intelligently. The simplest method might be to make a continuous record on a paper chart recorder as a given tape is played through at each Analyser setting. However, if all the recordings were analysed onto paper charts in this way the result would be such a mass of paper as to be practically unmanageable. For the analyses to be useful they must be combined in a much more economical representation. Integrating the output from a given frequency interval over the entire duration of the recording would give an average value which would be useful for some purposes. The integration could be done electronically, or by measuring the area under the line on a paper chart.

However, besides knowing the average level of noise in a given frequency interval, it might also be important to know the types of noise signal present ----- whether perfectly random, uniform, or in bursts of characteristic shape and duration. For this a more complex representation would be required. The best form would probably be that used in the "sound spectrograph" developed in the Bell Telephone Laboratories and described by R. K. Potter (Proc. I.R.E., 39, 1067-1069 Sept 1951). The sound spectrum is displayed as a shaded area with time as abscissa, frequency as ordinate,

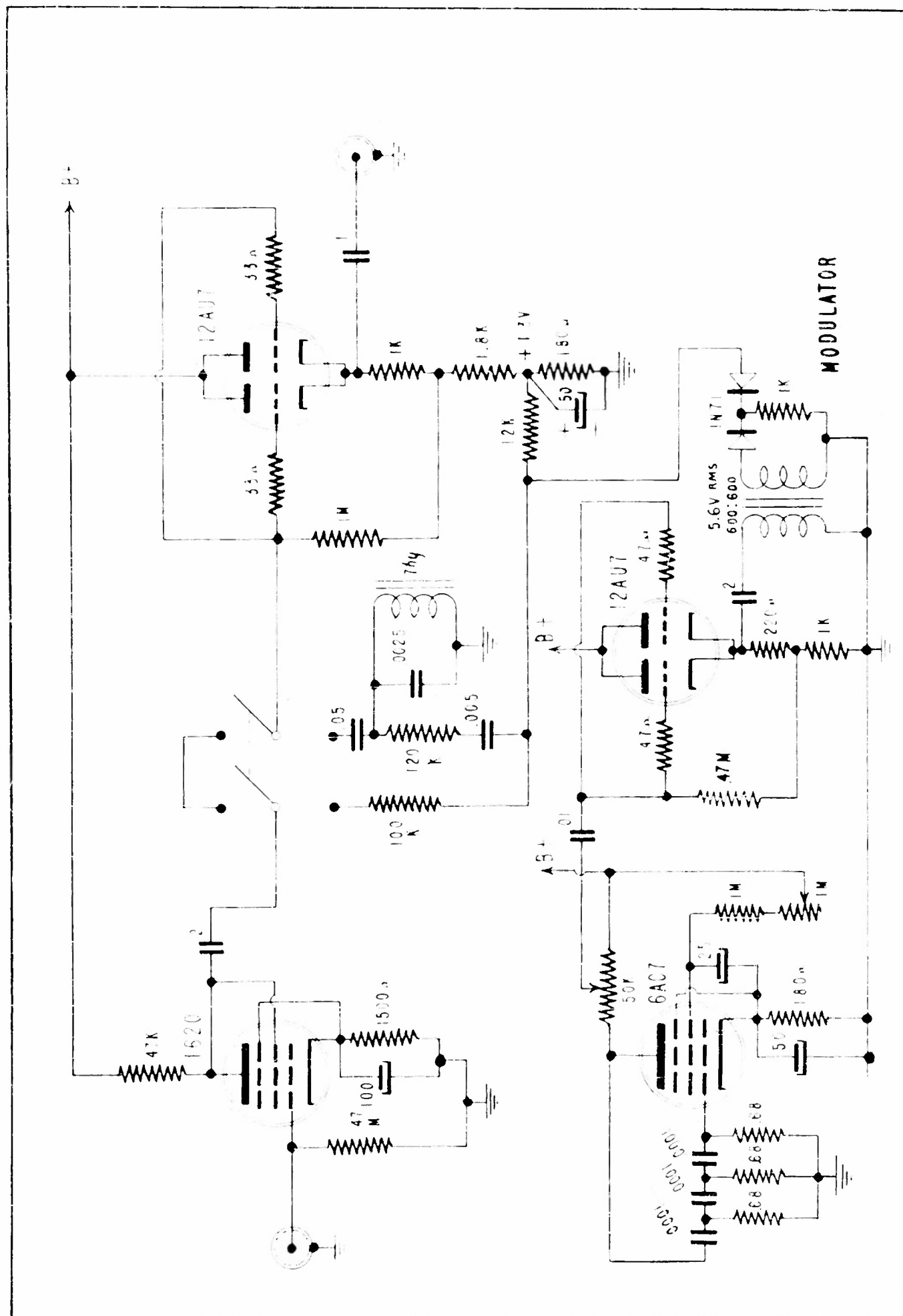
and amplitude as a modulation in density. This idea might be approximated by means of an Esterline-Angus recorder by combining the following features:

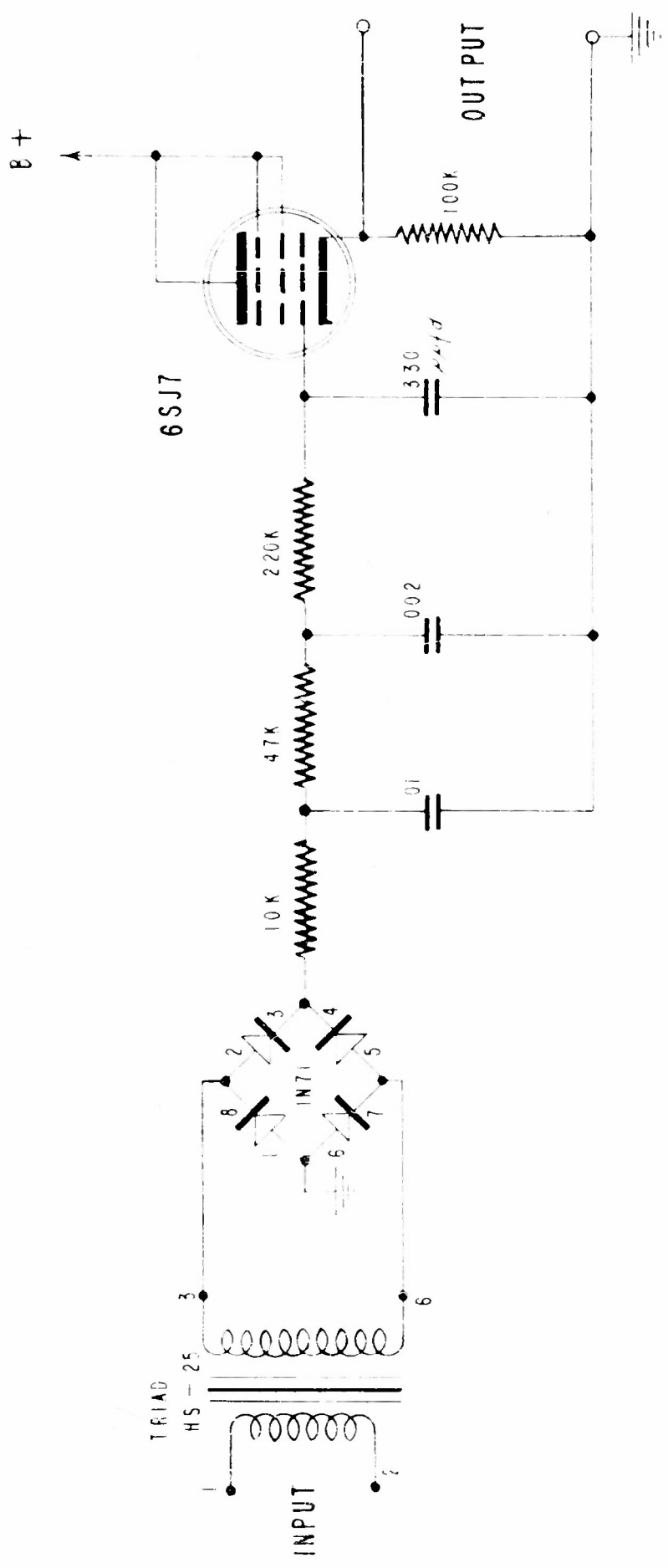
- (a) a direct-current bias, adjustable to displace the pen across the chart in small steps, each step corresponding to one setting of the frequency Analyser.
- (b) a low-frequency current to oscillate the pen with small amplitude about the average position, the amplitude of oscillation being proportional to the output of the Analyser, and the frequency of oscillation related to the chart speed so that the pen inks in a more or less solid ribbon of varying width.

The magnetic tape and the paper chart would have to be re-wound and started again in careful synchronism for each Analyser setting. To cover the spectrum from, say, 40 to 100 c/s, with each Analyser setting one resolution width from the next, would require about 65 settings.

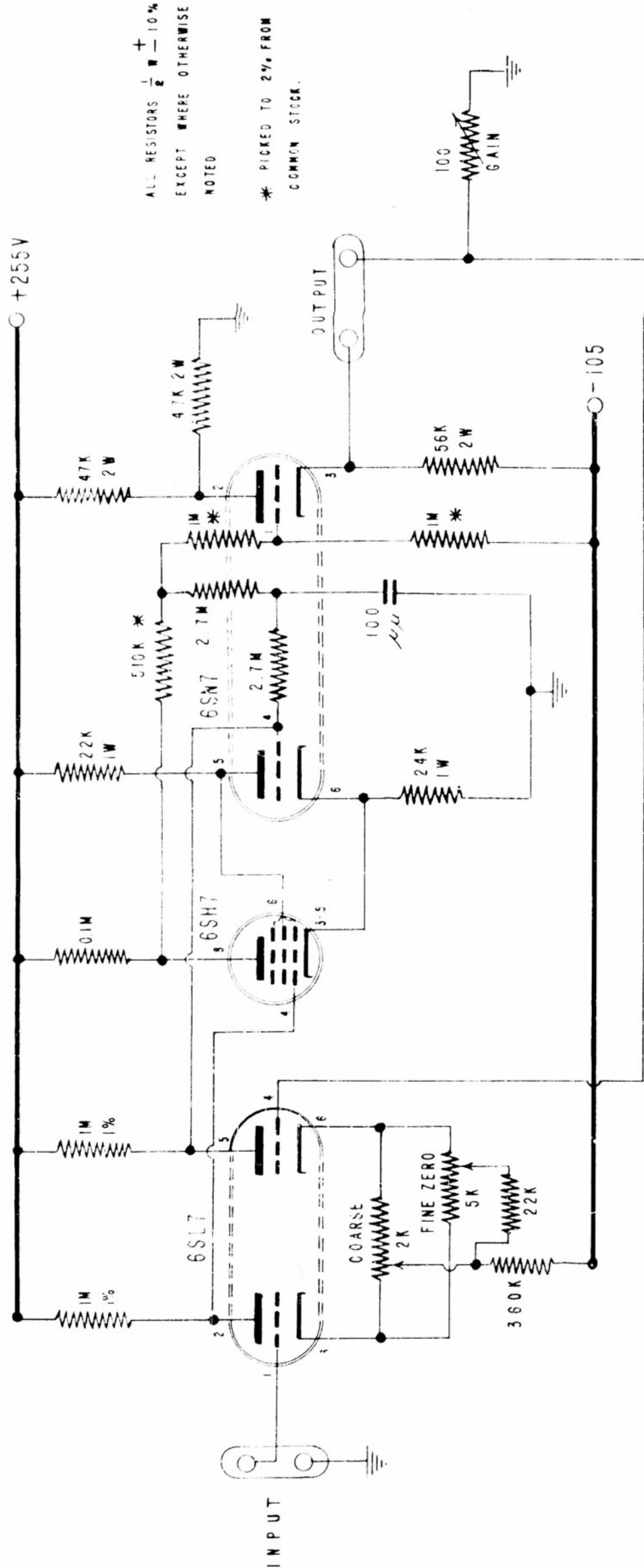
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DIAGRAMS



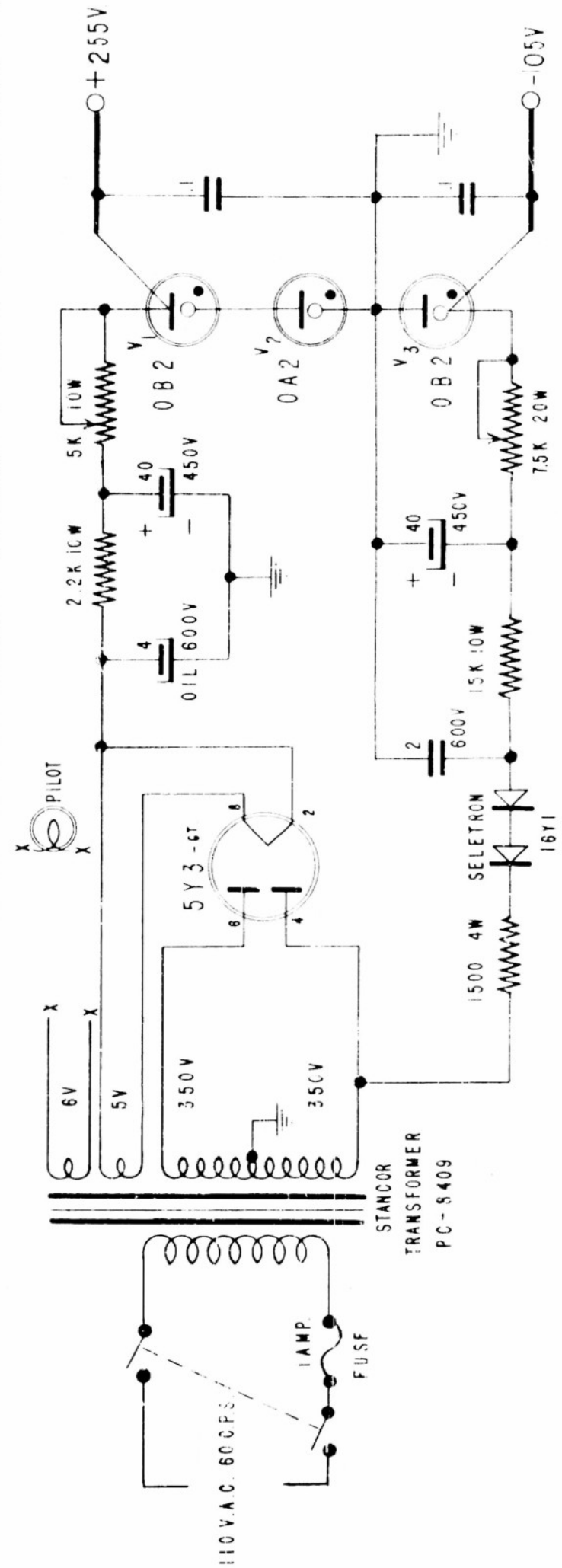


DEMODULATOR



ALL RESISTORS $\frac{1}{2}$ W - 10%
EXCEPT WHERE OTHERWISE
NOTED

* PICKED TO 2%, FROM
COMMON STOCK.



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